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THE FRAGMENTATION OF LIQUID C.W. AGENTS.

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(i) INTRODUCTORY.

The dispersal of many C.W. agents other than non-persistent gases usually involves the discharge of liquid from a weapon. The liquid may be ejected and broken up by an explosive charge (shell, bombs) or be fragmented by impact with an air stream (aircraft spray). The degree of dispersion which is desirable depends upon the nature of the C.W. agent; interest chiefly attaches to the two extreme cases, viz.

    (a) fine dispersion to produce a non-persistent cloud.

    (b) coarse dispersion to produce drops of sufficient size to give harmful effects on personnel or to contaminate ground or stores, etc.

(a) concerns the dispersion of agents which are intended to act quickly, e.g. D.C. or which, owing to their lack of volatility, cannot be dispersed by other means, e.g. T.654 (di m-amino phenyl stibinous oxide).

(b) chiefly concerns vesicants for which there is a minimum size of drop which will produce vesication through clothing. A coarse dispersion may also be necessary in the production of smoke curtains by aircraft to ensure that these curtains reach ground level

(ii) EMPIRICAL RESULTS.

(a) **Fine dispersion. (Shell and bombs).** There is no difficulty in attaining a satisfactory degree of dispersion with non-viscous liquid chargings in shell and bombs. With gunpowder bursters a mean drop size of 50 μ is obtained and with H.E. bursters the mean size is 10-20 μ. The violence of the explosion is sufficient, however, to give the cloud considerable vertical height (c.100 ft.) so that most of the C.W. agent is wasted. This method of dispersion is, therefore, inefficient, and can only be used with C.W. agents of high potency. If methods could be devised to produce a cloud of smaller height, but with the same degree of dispersion, they would be of great value and would enable a number of substances for which there is at present no satisfactory method of dispersion, to be used as C.W. agents.

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<u>Coarse dispersion.</u> (I) Shell and bombs. When vesicants (Notably mustard gas) are dispersed from air-burst shell it is desirable to convert as much as possible of the charging into drops of an efficient size. The desirable range for mustard gas is approximately between 1 nand 5 mm. in diameter. The lower limit is set by the fact that single drops smaller than 1.5 mm. will not produce with certainty vesication through service clothing. As the drop size increases, the intensity of the burn increases rapidly, but the number of drops per round and the density of drops per metre^2 of target decreases rapidly. The upper limit of 5 mm. diameter is a practical compromise between these opposing conditions.

Attempts to obtain the optimum size distribution have been concerned with (1) design of weapon and (2) modification of the physical properties of the charging. As regards (1) the base ejection type of shell has been developed with a piston in the head of the shell actuated by a small powder burster. This piston ejects the liquid from the shell after the lightly held base-plate has been pushed off. Even with this arrangement the drops produced by production mustard gas (unthickened) are, apart from vapour effects and attack on the bare skin, much too small to be of value against clothed personnel.

As regards (2) it has been found that increase of the viscosity of the charging has a marked effect on the drop size. By the addition of alloprene the viscosity of the fluid can be raised to 12 poises at 10°C. and the drop size distribution thus produced is given in table I below under "viscous charging". This appears to be the practical limit of viscosity which can be used; more viscous chargings tend to produce ballistic instability in the shell and give rise to incorporation and charging troubles.

In addition such very viscous chargings penetrate clothing less rapidly.

More recently it has been found that incorporation of raw rubber in a mixture of production mustard gas and carbon tetrachloride gives a system which has notable resistance to fragmentation by explosive shock. Rubber is insoluble in mustard gas and a mixture of equal volumes of mustard gas and carbon tetrachloride is approximately the limiting mixture which will allow rubber to swell indefinitely and disperse. The resultant solution has a relatively low viscosity (about 1-2 poise) but has a definite elasticity of form; this seems to be the property which determines the resistance of the solution to disruption and these systems are therefore termed "gels" although they are mobile fluids. The drop size distribution of a gel containing 1½% by weight of rubber is quoted in Table I. By increasing the amount of rubber the drop spectrum can be shifted to larger diameter; with 8% of rubber the charge is ejected in the form of a few large lumps with diameters of some centimetres.

TABLE I.

Drop Size Distribution from Air-burst
25-pr. Shell.
% by weight of charging.

Drop Diameter.	Viscous. H.M.V. 12p.	Viscous. H.B.D.V. 12p.	Gel. H.M. 1½% Rubber.
0-1 mm.	96%	68.5%	3%
1-2 "	4%	37%	34%
2-3 "	0	0.5%	45%
3-4 "	0	0	16%
4-5 "	0	0	trace.
5-6 "	0	0	2%

H.M.V. 12p. is crude mustard gas diluted with 8-10% of mono-chlorobenzene and thickened to 12 poise viscosity with alloprene.

H.B.D.V.12p. is mustard gas made by the "direct" process with benzene as solvent and thickened to 12 poise viscosity with alloprene.

H.M.1½% Rubber. is a mixture of equal volumes of crude mustard gas and carbon tetrachloride in which 1½% by weight of raw rubber has been dispersed.

(b) Coarse dispersion (II) Aircraft spray.
Liquids discharged from aircraft flying at speeds of 200 miles per hour are disrupted by impact with air. Here again the use of viscous liquids and of gels gives a degree of control of drop size. Some typical figures are quoted in Table II.

TABLE II.

Drop Size distribution in
Aircraft Sprays.

% by weight of charging. (Methyl Salicylate (M.S.) - mustard substitute).

Diameter in mm.	Viscous. 6 poise.	Rubber Gel.
0-1	30%	1%
1-2	51%	11%
2-3	18%	19%
3-4	1%	24%
4-5	0	20%
5-6	0	21%
6-7	0	4%

The viscous chargings whilst giving only a moderately
satisfactory drop size distribution have a satisfactory life
when stored at tropical temperatures. The rubber gels which
give a better drop size spectrum deteriorate rather rapidly in
hot storage. Neoprene G. and a few other substances have been
found which give suitable gels and are probably stable in hot
storage. These are now being studied but are not so readily
available as raw rubber in this country.

The rubber "gels" used in trials for aircraft spray are
rather different in character from those used in shell. They
contain about 2% by weight of rubber in a mixture of equal
volumes of mustard gas and carbon tetrachloride and undergo
some mastication during their preparation. They have little
elasticity and probably control drop size by the formation of
an initial tough membrane when the liquid is exposed to a
current of air.

(iii) THEORETICAL CONSIDERATIONS.

The fragmentation of liquids by explosive shocks or by impact
with an air stream is obviously a complex phenomenon and a more
fundamental study of the factors which bring about the disruption
might give results which would considerably modify the design and
improve the efficiency of C.W. weapons. The broad facts which have
been arrived at empirically have been summarised in Section ii; in
this section some further experiments aimed at a more detailed
knowledge of the process will be described and tentative theories
will be outlined which may be useful in suggesting new lines for
investigation.

The problem of aircraft spray has already been attacked math-
ematically in Porton Departmental Report No.146. The theory of
ripples on a liquid surface over which a steady stream of air is
flowing shows that ripples of certain wave-lengths are hydrodynamic-
ally unstable and grow rapidly in amplitude. An approximate theory
of break-up is developed by correlating the wave length of the most
unstable ripple with the diameter of the most frequent drop in the
drop spectrum. This leads to the conclusion that the "main" drop
will have dimensions proportional to

$$\mu^{2/3} \ V^{-4/3} \ T^{1/3}$$

where μ is the viscosity of the liquid, T its surface tension and V
is the wind velocity. The elaboration of this theory predicts a
drop size distribution which is in fair agreement with that found
experimentally. The theory has been tested for a range of values
of μ and V. Change in V gives a variation in drop size which is in
satisfactory agreement with the theory; there is less satisfactory
agreement with the results in which μ is varied. The surface ten-
sion T cannot be varied to any considerable extent with organic
liquids. If a tough surface skin is formed with the rubber gels
referred to in (ii) this will in effect give a very large increase
in T; this may account for the results observed with these charg-
ings.

Fragmentation of liquids ejected from weapons by an explosive
charge presents a different problem. It is clear that the fragmenta-
tion occurs before, or at the moment of opening of the container; sub-
sequent shattering by projection through the air is of little import-
ance.

Direct evidence for this conclusion is given by high speed cinematography of bursting weapons carried out by the French. The cloud of fine spray is evident at the moment of ejection.

Further evidence has been obtained from experiments with Bomb ground 6 lb. which Dr. G.S. Hartley has found useful for small scale work. This bomb consists of a thin cylindrical steel container about 4" in diameter and 3" long and holds about 1 litre of liquid. One end is closed by a welded steel plate which is thrown off when the bomb is functioned; the small bursting charge (6 gms. of gunpowder) is situated at the other, stronger end of the bomb.

If such a bomb is functioned at an angle of 45° so as to throw the ejected liquid into the air, it is found in still air that none of the liquid travels further than 20 yds. from the bomb. Some large drops up to 5 mm. diameter are found near the bomb and some smaller ones at various distances mostly near the 20 yd. limit. The bulk of the liquid (non-viscous) is shattered into very fine drops which fall at intermediate distances. Now it is easily possible by means of a coarse spray to throw large water drops more than 20 yards without the production of fine spray en route. Hence the high degree of fragmentation found in the bomb is not mainly due to projection of the liquid through the air.

In another experiment the steel end plate of the bomb was replaced by a rubber diaphragm which could stretch and would take a longer time to burst. Much coarser fragmentation was given by this arrangement. This may be interpreted as follows.

The liquid is split into fine particles by the explosive shock; if these are held together for a short time interval they will coalesce and form larger aggregates.

A third experiment was made with three miscible layers of liquids of different density and coloured with different dyes. It was found that the large drops near the bomb were all produced by the lowest layer nearest the burst, and that only a very small number of drops showed any mixing of the layers. This indicates that in this weapon fragmentation is least for that part of the liquid which is the last to leave the bomb and shows clearly that fragmentation occurs before there is any mixing of the contents of the bomb by turbulence.

These preliminary experiments have led to the following general picture of the process of fragmentation which may be useful in directing further research. In short fragmentation is caused by cavitation of the liquid. It is not quite clear whether the passage of the explosive shock wave through the fluid leaves behind a cavitated liquid which is then ejected before the cavities have time to collapse or whether it is more nearly true to regard the contents of the bomb as a liquid under compression which on sudden release of the pressure when the container opens forms cavities. In either case fragmentation is due to cavitation which in turn is due to expansion of the liquid giving tensions in excess of the tensile strength of the liquid.

Consideration of the results of experiments on cavitation produced by intense supersonic waves indicates that both compression waves and release from general pressure may play a part. Cavitation in a liquid by such waves can be inhibited (a) by outgassing which raises the effective tensile strength and (b) by applying external pressure which can act by reducing the amplitude of the tension phase of the ultrasonic wave to a value less than the tensile strength. This is shown in the diagram alongside. The full curve

+p
O
-p

Tensile strength.
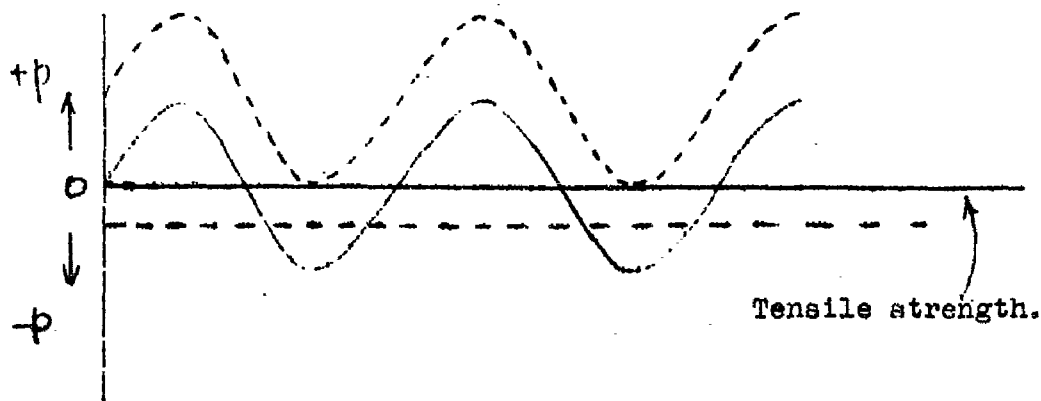
indicates the instantaneous pressures and tensions along
the track of the wave with an initial pressure zero whilst
the dotted curve represents the conditions when a considerable
general pressure is maintained in the fluid.

When a fluid is exposed to explosive shock there will
be both a general rise of pressure and the formation of a
pattern of intense compression waves moving through the
liquid with the velocity of sound and reflected from the
walls of the vessel. Some direct evidence has been obtained
from oscillograph piezo gauge studies. Up to the present it
has not been possible to obtain gauges which will withstand
the pressures used to burst weapons but with a tourmaline
gauge and a small explosive charge which does not open the
weapon some pressure-time curves have been obtained of the
form shown in the diagram. These show a general rise in
pressure with superimposed higher frequency pressure waves
which have a frequency of the
right order of magnitude for
sound waves reflected to and fro
in the weapon. When the weapon
opens cavitation can be produced

.4
.3
.2
.1

tons / sq. inch.

Milliseconds.

1   2
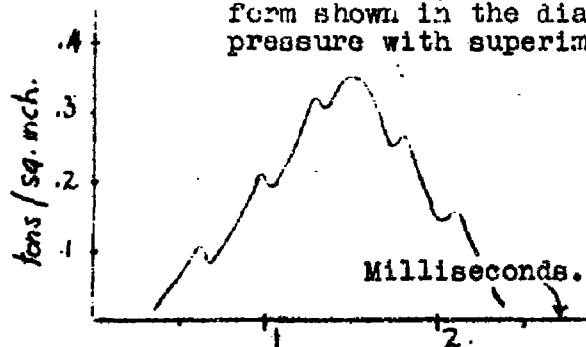
(a) ty release of overall pressure, (b) locally by the ten-
sion phase of the compression waves and (c) by reflection
of these waves at liquid-air surfaces giving a change of
phase from compression to tension. Much further work is
required to ascertain the relative importance of these
processes and it is desirable to develop gauges which
will withstand higher pressures and increase materially
the speed of the recording oscillograph and camera.

The production of cavities depends clearly on the ten-
sile strength of the liquid and the amount of energy which
is stored in compression. It is found in fact that water
which has a low compressibility and a high tensile
strength is fragmented much less than organic liquids
under comparable conditions. Of these two properties
compressibility cannot be controlled and tensile strength
can only be increased notably by outgassing (which is
impracticable) or by dissolving in the liquid certain
substances of high molecular weight which also notably
increase the viscosity. Indeed it is not yet clear
whether the improvement found with viscous liquids is
due to the viscosity per se or is partly due to the con-
comitant increase in tensile strength.

A more detailed consideration of the process of fragmentation is helpful in discussing this question. At the moment of explosion the cavities in the liquid must be very small since they can only occupy a small fraction of the total volume. When the weapon opens they will expand rapidly and successive stages may be pictured as in diagrams, 1., 2., and 3.
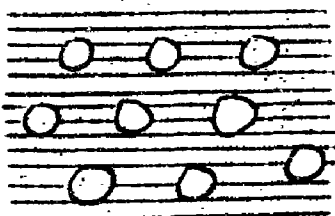

1. Compressed liquid.
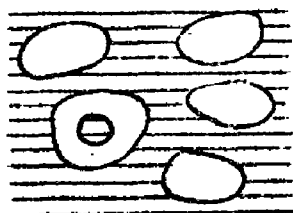
2. Expanded liquid with numerous small cavities.

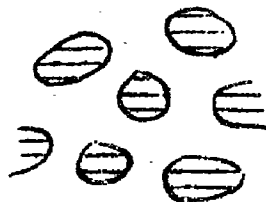3. Liquid free of container cavities rapidly enlarging.

Further rapid expansion of the cavities leads to an unstable vapour-in-liquid froth which inverts to a stable "liquid-in-vapour" spray as in diagrams 4, 5 and 6.


4.   5.   6.

It is unlikely that increase in viscosity will tend to reduce the number of cavities in stage 2. It is more likely to have the reverse effect since retardation of the rate of growth of the cavities first formed will mean that they do not so rapidly relieve the strain on the liquid and others may form later. Any increase in tensile strength produced by the thickening agent will of course tend to reduce the number of initial cavities. An effect of viscosity in reducing the degree of shatter is more probable in stages 3 - 5. The kinetic energy of the liquid particles which are moving away from one another will be degraded to heat more rapidly in a viscous fluid and the average size of the cavities will be less. Fewer of the cavities will reach an unstable size and there will be greater chances of coalescence or collapse to the original state.

So far, only normal "Newtonian" liquids have been considered. If the liquid shews structural viscosity - or thixotropy with rapid accommodation - it would be the low value of the viscosity corresponding to the high rate of shear which should be effective in controlling break-up. In harmony with this view it has been found that a stiff but highly thixotropic paste of bentonite in water is fragmented almost as much as pure water.

The gels whihh have been found so effective in controlling fragmentation are characterised by having marked elasticity of form. This property may play an important part in stages 3 - 5 of the fragmentation process. With a low viscosity expansion will proceed as in the case of a normal liquid but the open structure 5 will have less tendency to invert to 6 since the elasticity will cause the incipient fragments to collect and assume their original form. Furthermore extended and indented

fragments produced at the later stages will recover a compact form with elastic gels but will split into a number of small fragments if they are composed of a non-elastic fluid. This is indicated diagrammatically below.
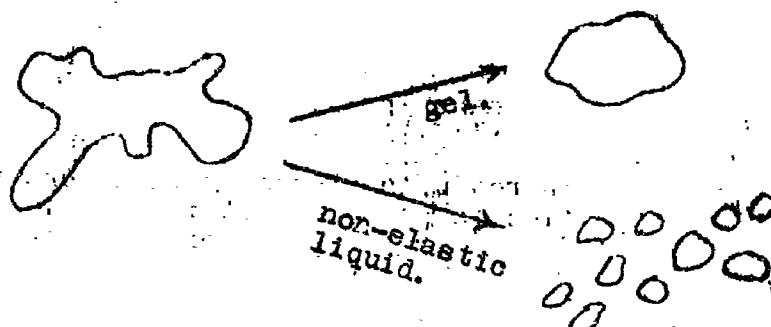
It must be stressed, however, that the elastic coefficient and the viscosity are not a complete description of the fluid gels which have been found to resist fragmentation. A table jelly for example has a much higher elastic coefficient for small displacements than the dilute rubber gels. Recovery from such displacements is rapid and complete with the table jelly but slow and incomplete with the rubber gels. Large displacements easily exceed the elastic limit of the table jelly which fractures; the rubber gel, on the other hand, can be stretched into very long "ropes" and maintained stretched for long periods without fracture. It seems to be this toughness and ropiness which gives the rubber gel its valuable properties and the development of the laboratory methods of testing which could be correlated with field tests would be of great value.

(b)   More recently work has been carried out by Professor Whytlaw-Gray, F.R.S. (V.728)   on   the fragmentation of liquids confined behind an aluminium diaphragm which is ruptured by an applied gas pressure. The course of the phenomenon has been followed by spark photography and pressures up to 130 atmospheres have been used. Experiments with double diaphragms have also been made and measurements of the size distribution and mass concentration of the dispersed liquid have been carried out.

The general conclusion reached at present is that the dispersion is due mainly to the formation of a bubble of gas with a thin outer film of liquid which rapidly expands and explodes. The next most important cause of breakup is the shearing of liquid by the passage of a rapid current of gas over its surface.

These experiments are continuing, and will include a study of the effect of gas pressures up to 1000 atm. High explosive bursters will be also examined.

SUMMARY AND CONCLUSIONS.

1. Empirical Results.

The drop size distribution of liquid chargings ejected from weapons can be controlled to some extent by increasing the viscosity of the charging and to a greater extent by the use of gel chargings.

Fine dispersion can be attained in shell and bombs when desired but loss in efficiency occurs because the cloud produced has too large dimensions in a vertical plane and too low a concentration at ground level.

2. Mode of Action.

The break-up of aircraft spray appears to be initiated by the formation of unstable ripples on the liquid surface in contact with the air stream.

The break-up of liquids ejected from shell and bombs seems to be initiated by cavitation caused by (a) sudden release from pressure and (b) passage of intense compression waves through the fluid.

3. Further investigations.
It is desirable to develop suitable gauges which could be used to determine pressure-time curves in bursting weapons. These might be valuable, not only for fundamental investigations, but also for the investigation of faulty performance and for the development of improved designs of weapons.

The above memorandum was prepared by Prof. S. Sugden, F.R.S.

(sgd) A.E. Childs,

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for Chief Superintendent, C.D. Exptl.Stn.

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